

β -decay half-lives of neutron-rich nuclei and matter flow in the r -process

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(Dated: October 3, 2012)

Abstract

The β -decay half-lives of neutron-rich nuclei with $20 \leq Z \leq 50$ are systematically investigated using the newly developed fully self-consistent proton-neutron quasiparticle random phase approximation (QRPA), based on the relativistic Hartree-Fock-Bogoliubov (RHFB) framework. Available data are reproduced by including an isospin-dependent proton-neutron pairing interaction in the isoscalar channel of the RHFB+QRPA model. With the calculated β -decay half-lives of neutron-rich nuclei, a remarkable speeding up of r -matter flow is predicted. This leads to enhanced r -process abundances of elements with $A \gtrsim 140$, an important result for the understanding of the origin of heavy elements in the universe.

PACS numbers: 23.40.-s, 21.60.Jz, 26.30.Hj, 21.30.Fe

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Nuclear β -decay plays an important role not only in nuclear physics but also in other branches of science, notably astrophysics and particle physics. In nuclei the investigation of β -decay provides information on the spin and isospin dependence of the effective nuclear interaction, as well as on nuclear properties such as masses [1], shapes [2], and energy levels [3]. In nuclear astrophysics β -decay half-lives set the time scale of the rapid neutron-capture process (r -process), and hence determine the production of heavy elements in the universe [4–6]. In particle physics β -decay was used to obtain the first experimental evidence of parity violation [7], and can be utilized to verify the unitarity of Cabibbo-Kobayashi-Maskawa (CKM) matrix [8, 9].

Important advances in the measurement of nuclear β -decay half-lives have been achieved in recent years with the development of radioactive ion-beam facilities, especially for nuclei near the neutron shell closures of 50 and 82 [10–12]. Quite recently β -decay half-lives of very neutron-rich Kr to Tc isotopes with neutron number between $N = 50$ and 82 have been measured [13]. The new experimental results indicate a systematic deviation from half-lives predicted by standard calculations based on the finite-range droplet model (FRDM) plus quasiparticle random phase approximation (QRPA). The effects of the newly measured β -decay half-lives on r -process nucleosynthesis have been investigated in Ref. [14], and it has been shown that the main effect is an enhancement in the abundances of isotopes with mass number $A = 110 - 120$, relative to abundances calculated using β -decay half-lives estimated with the FRDM+QRPA.

Most neutron-rich nuclei relevant for the r -process are still out of the reach of experimental facilities and, therefore, r -process calculations are based on theoretical predictions for β -decay half-lives. Theoretical investigations of the nuclear β -decay started in the 1930's, with the introduction of the famous Fermi theory [15]. Two types of microscopic approaches are nowadays mainly used in large-scale calculations of nuclear β -decay half-lives, that is, the shell model and the proton-neutron QRPA. Specifically the shell model has been applied to calculation of β -decay half-lives for nuclei at $N = 50, 82, 126$ and reproduces well the experimental half-lives [6, 16, 17]. However, shell-model calculations for heavy nuclei away from the magic numbers are not feasible yet because of extremely large configuration spaces. Compared to this approach, the proton-neutron QRPA can be applied to arbitrary heavy systems. Nuclear β -decay calculations have been carried out using the QRPA based on the FRDM [18], the extended Thomas-Fermi plus Strutinsky integral (ETFSI) model [19], the

Skyrme Hartree-Fock-Bogoliubov (SHFB) model [20], and the density functional of Fayans (DF) [21].

Covariant density functional theory (CDFT) has been applied very successfully to the description of a variety of nuclear structure phenomena [22–24]. The CDFT framework naturally includes the nucleon spin degree of freedom, and the resulting nuclear spin-orbit potential automatically emerges with the empirical strength, thus producing a good agreement with the experimental single-nucleon spectrum [25]. Based on the relativistic Hartree-Bogoliubov (RHB) model in the CDFT framework, the QRPA has been formulated [26] and employed in the calculations of β -decay half-lives of neutron-rich nuclei in the regions of $N \approx 50$ and $N \approx 82$ [27, 28].

To reliably predict properties of thousands of unknown nuclei relevant to the r -process, the self-consistency of the QRPA approach is essential. Only recently the fully self-consistent relativistic RPA has been formulated based on the relativistic Hartree-Fock (RHF) theory [29]. Using the RHF+RPA model excellent agreement with data on the Gamow-Teller (GTR) and spin-dipole resonances in doubly magic nuclei has been obtained, without any readjustment of the parameters of the covariant energy density functional [29, 30]. Recently also the relativistic Hartree-Fock-Bogoliubov (RHFB) theory has been developed, providing a unified description of both mean field and pairing correlations [31, 32].

In this Letter we report the implementation of a fully self-consistent proton-neutron QRPA based on the RHFB theory, and its first systematic application in calculations of β -decay half-lives of neutron-rich nuclei with $20 \leq Z \leq 50$, extending over the whole r -process path from $N = 50$ to $N = 82$. The effect on r -process nucleosynthesis simulations is also investigated using the classical r -process model.

The details of the QRPA formalism in the canonical basis can be found in Refs. [20, 26]. In the RHFB+QRPA model both the direct and exchange terms are taken into account, so the matrix elements of the particle-hole (p - h) V^{ph} and particle-particle (p - p) V^{pp} residual interactions are respectively written as

$$V_{pn p' n'}^{ph} = \int \int d\mathbf{r}_1 d\mathbf{r}_2 f_p^+(\mathbf{r}_1) f_{n'}^+(\mathbf{r}_2) \sum_{\phi_i} V_{\phi_i}(1, 2) [f_{p'}(\mathbf{r}_2) f_n(\mathbf{r}_1) - f_n(\mathbf{r}_2) f_{p'}(\mathbf{r}_1)], \quad (1)$$

$$V_{pp'n'}^{pp} = \int \int d\mathbf{r}_1 d\mathbf{r}_2 f_p^+(\mathbf{r}_1) f_n^+(\mathbf{r}_2) \sum_{T=1,0} V_T(1, 2) [f_{n'}(\mathbf{r}_2) f_{p'}(\mathbf{r}_1) - f_{p'}(\mathbf{r}_2) f_{n'}(\mathbf{r}_1)] . \quad (2)$$

p, p' , and n, n' denote proton and neutron quasiparticle canonical states, respectively, and ϕ_i and T denote corresponding coupling channels. $f_{p(n)}$ are canonical wave functions extracted from the RHFB calculations.

Because of the presence of exchange terms, the proton-neutron QRPA interaction contains terms generated not only by the isovector meson exchange (ρ and π), but also by the exchange of isoscalar mesons (σ and ω). As in Ref. [29] the pionic zero-range counter term introduced to remove the contact part of the pseudovector π -N coupling reads

$$V_{\pi\delta}(1, 2) = g' \left[\frac{f_\pi}{m_\pi} \vec{\tau} \gamma_0 \gamma_5 \boldsymbol{\gamma} \right]_1 \cdot \left[\frac{f_\pi}{m_\pi} \vec{\tau} \gamma_0 \gamma_5 \boldsymbol{\gamma} \right]_2 \delta(\mathbf{r}_1 - \mathbf{r}_2) , \quad (3)$$

where the self-consistency of the model requires $g' = 1/3$. For the isovector ($T = 1$) p - p channel the pairing part of the Gogny force D1S [33] is consistently used both in the RHFB and QRPA calculations. For the isoscalar ($T = 0$) proton-neutron pairing in the QRPA we employ a similar interaction that was previously used in Refs. [20, 27, 28]:

$$V_{T=0}(1, 2) = -V_0 \sum_{j=1}^2 g_j e^{-[(\mathbf{r}_1 - \mathbf{r}_2)/\mu_j]^2} \hat{\Pi}_{S=1, T=0}, \quad (4)$$

with $\mu_1 = 1.2$ fm, $\mu_2 = 0.7$ fm, $g_1 = 1$, $g_2 = -2$. The operator $\hat{\Pi}_{S=1, T=0}$ projects onto states with $S = 1$ and $T = 0$. V_0 is the overall strength of the $T = 0$ proton-neutron pairing.

With the individual transition strengths B_m obtained from QRPA calculations, the β -decay half-life of an even-even nucleus is calculated in the allowed Gamow-Teller approximation using the expression:

$$T_{1/2} = \frac{D}{g_A^2 \sum_m B_m f(Z, E_m)}, \quad (5)$$

where $D = 6163.4 \pm 3.8$ s and $g_A = 1$. The sum runs over all final states with an excitation energy smaller than the Q_β value. The integrated phase volume $f(Z, E_m)$ can be written as

$$f(Z, E_m) = \int_{m_e}^{E_m} p_e E_e (E_m - E_e)^2 F_0(Z, E_e) dE_e, \quad (6)$$

where p_e , E_e , and $F_0(Z, E_e)$ denote the emitted electron momentum, energy, and Fermi function, respectively [6]. The β -decay transition energy E_m , that is, the energy difference

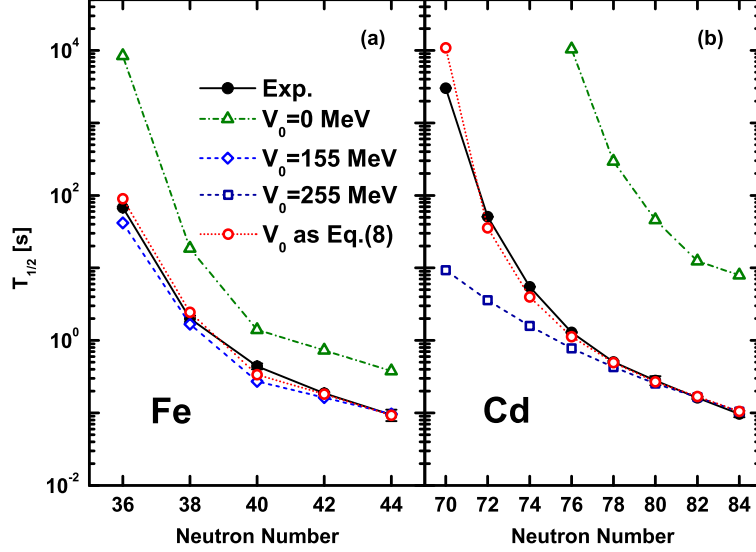


FIG. 1: (Color online) Nuclear β -decay half-lives of Fe (left) and Cd (right) isotopes, calculated with the PKO1 effective interaction [34], compared with the experimental values [10]. Open triangles, diamonds, and squares denote values obtained using the RHF+QRPA with the strength parameter of the $T = 0$ pairing: $V_0 = 0, 155$, and 255 MeV, respectively. The RHF+QRPA values obtained with the V_0 of Eq. (8) are denoted by open circles.

between the initial and final state, is calculated using the QRPA:

$$E_m = \Delta_{np} - E_{\text{QRPA}}, \quad (7)$$

where E_{QRPA} is the QRPA energy with respect to the ground-state of the parent nucleus and corrected by the difference of the neutron and proton Fermi energies in the parent nucleus [20], and Δ_{np} is the neutron-proton mass difference.

Nuclear β -decay half-lives are very sensitive to the $T = 0$ proton-neutron pairing interaction, and its strength V_0 is determined by adjusting QRPA results to empirical half-lives [20, 27, 28]. Taking ^{70}Fe and ^{130}Cd as reference nuclei for the two mass regions, the value of V_0 is determined as 155 MeV and 255 MeV, respectively. Using these two values, the calculated half-lives of Fe and Cd isotopes are shown in Fig. 1. For comparison, the experimental values and the results of a calculation without the $T = 0$ pairing are also displayed. One notices that the β -decay half-lives calculated without the inclusion of $T = 0$ pairing are systematically much longer than the experimental half-lives, both for Fe and Cd isotopes. In previous studies a constant value of V_0 was taken for one isotopic chain or one mass region, determined by adjusting to the known half-lives of selected nuclei in the isotopic

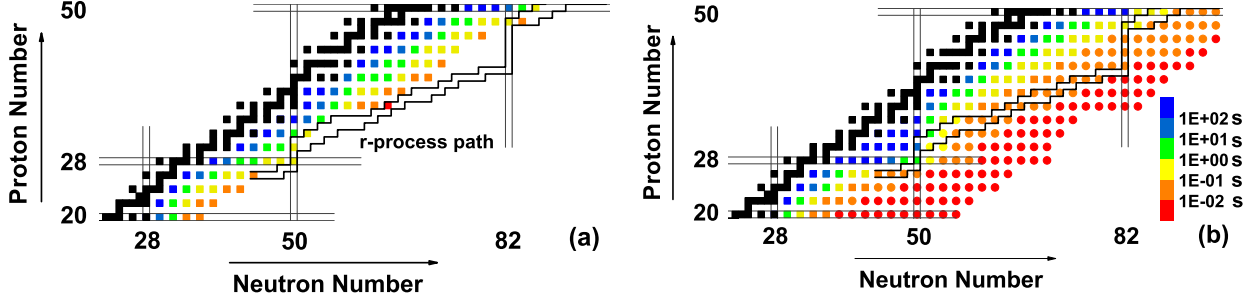


FIG. 2: (Color online) Contour map of β -decay half-lives for the $Z = 20 - 50$ even-even nuclei. The experimental half-lives [10, 13] and the RHF+QRPA results obtained with the effective interaction PKO1 are shown in panel (a) and panel (b), respectively. For reference the r -process path is also displayed.

chain [27], or several nuclei in the same mass region [20]. This procedure, of course, limits the predictability of the model. Moreover, as shown in Fig. 1 for the Cd isotopes, when V_0 is determined by the β -decay half-life of ^{130}Cd the calculated results underestimate the half-lives of $^{118,120,122}\text{Cd}$. This indicates that the half-lives of an isotopic chain cannot always be reproduced using a constant value V_0 , and points out to a possible isospin-dependence of V_0 . In the present work, therefore, we employ the following ansatz for an isospin-dependent pairing strength:

$$V_0 = V_L + \frac{V_D}{1 + e^{a+b(N-Z)}}, \quad (8)$$

and adjust the parameters to reproduce the known half-lives of even-even nuclei with $20 \leq Z \leq 50$: $V_L = 134.0$ MeV, $V_D = 121.1$ MeV, $a = 8.5$, and $b = -0.4$.

With the isospin-dependent strength Eq. (8) of the proton-neutron pairing interaction, the calculated β -decay half-lives of both the Fe and Cd isotopic chains are in excellent agreement with data. Encouraged by this success, we proceed to calculate the half-lives of even-even nuclei with $20 \leq Z \leq 50$ using the RHF+QRPA model, and compare the theoretical values to data in Fig. 2. Even though a wealth of new data on nuclear β -decay half-lives have been obtained in recent years, only few measurements can reach the r -process path, especially for the r -process path around $N = 82$. The present RHF+QRPA calculation yields results in good agreement with the data, especially for nuclei with half-lives $T_{1/2} < 1$ s. Only an overestimation of half-lives for Ni, Zn, and Ge isotopes near stability line is noticed. The longer half-lives predicted for Ni isotopes is a common problem in self-consistent relativistic QRPA calculations [27, 28]. For Zn and Ge isotopes, the differences

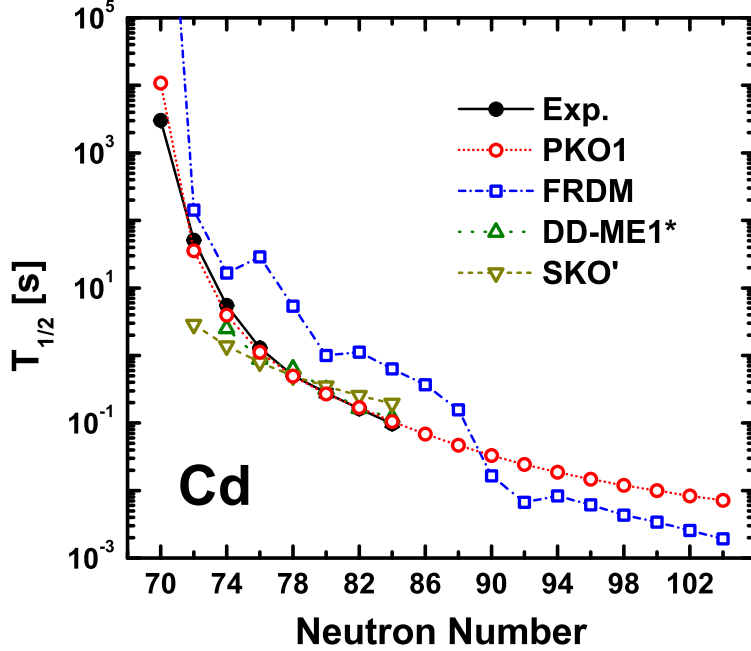


FIG. 3: (Color online) Nuclear β -decay half-lives of Cd isotopes calculated in the RHFB+QRPA framework using the isospin-dependent proton-neutron pairing interaction, and the effective interaction PKO1. For comparison, the experimental values [10], as well as the theoretical results obtained in the RHB+QRPA model with the effective interaction DD-ME1* [27], the SHFB+QRPA calculation with the effective interaction SkO' [20], and the FRDM+QRPA calculation [18], are also shown.

between present results and the experimental values are remarkably reduced as the neutron number increases. Taking ^{84}Ge for example, the theoretical result is 1.3 s, rather close to the experimental value: 0.954 ± 0.014 s.

In Fig. 3, the calculated β -decay half-lives of a sequence of Cd isotopes using RHFB+QRPA approach are displayed in comparison with measured values and previous theoretical results. One notices that the RHFB+QRPA model reproduces in detail the empirical β -decay half-lives, whereas the RHB+QRPA [27] and SHFB+QRPA [20] calculations that used a constant proton-neutron pairing strength cannot yield the appropriate isospin dependence of β -decay half-lives. The global FRDM+QRPA calculation [18] systematically overestimates the measured half-lives of Cd isotopes. It has been pointed out that the overestimation of half-lives in the FRDM+QRPA approach can be at least partially attributed to the omission of the $T = 0$ pairing [20]. This is further confirmed in this work as the

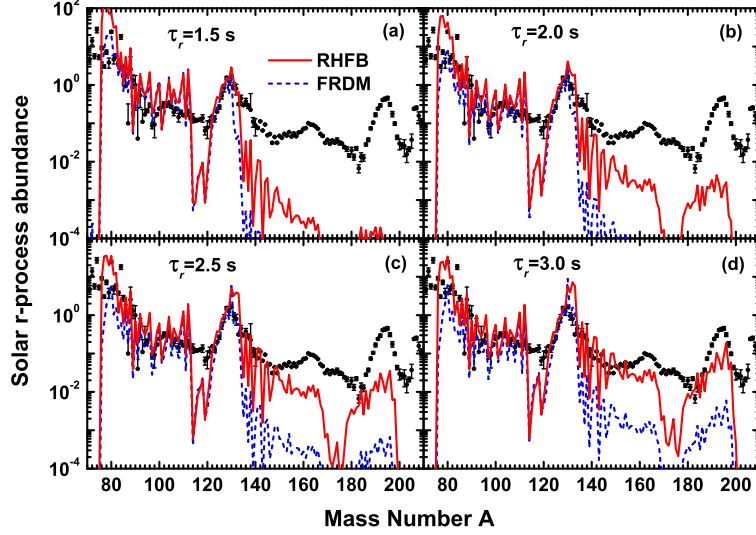


FIG. 4: (Color online) The impact of nuclear β -decay half-lives on the calculated r -process abundance. The solid (dashed) curves correspond to r -process abundance calculated with the RHFB+QRPA (FRDM+QRPA) β -decay half-lives in comparison with the data denoted by the points. In all calculations, nuclear masses are taken from the mass evaluation [10] if available, otherwise predictions of RMF mass model [36] are employed. Panels (a)-(d) correspond to the times $\tau_r = 1.5, 2.0, 2.5$, and 3.0 s, respectively.

half-lives are systematically reduced with the inclusion of $T = 0$ pairing. Furthermore, for the Cd isotopes with $N \geq 90$ the FRDM+QRPA calculation predicts shorter half-lives compared to the RHFB+QRPA. In the FRDM a shape transition occurs from the spherical ^{136}Cd to the deformed ^{138}Cd with the quadrupole deformation $\beta_2 = 0.125$. Therefore, the shorter half-lives for Cd isotopes with $N \geq 90$ in FRDM+QRPA calculation may be due to the effect of nuclear deformation. Similar systematics are also found for the Zr, Mo, Ru, Pd isotopes where shape transitions occur. However, it should be noted that a recent self-consistent QRPA calculation that used a Skyrme interaction has shown the opposite trend [35].

To analyze the impact of the predicted β -decay half-lives on r -process abundances, we have also performed a classical r -process calculation similar to those in Refs. [37, 38], with neutron density $n_n = 10^{22} - 10^{24} \text{ cm}^{-3}$ and temperature $T = 1.5 \times 10^9 \text{ K}$. Figure 4 displays snapshots of r -process abundance for different process time τ . It is shown that the half-lives calculated with RHFB+QRPA model (in solid lines) produce a faster r -matter flow at the

$N = 82$ region, thus yield higher r -process abundances of elements with $A \gtrsim 140$. By summing up the half-lives of r -path nuclei at $N = 82$, one can roughly estimate the time when the r -process passes the $N = 82$ shell. Based on the RHFB+QRPA results, this time is speeded up to 0.25 s from the 1.29 s predicted by the FRDM+QRPA calculation. This is an important result for the estimate of the duration of the r -process, and hence the origin of heavy elements in the universe. In addition, it is found that the abundance at $A \sim 80$ is higher using the RHFB+QRPA result, a result that can be easily understood because it takes more time to pass the r -path nuclei ^{78}Ni and ^{80}Zn and, as a result, higher abundances are accumulated.

In summary, this work introduces the fully self-consistent proton-neutron quasiparticle random phase approximation (QRPA), based on the relativistic Hartree-Fock-Bogoliubov (RHFB) framework. Using an isospin-dependent proton-neutron $T = 0$ pairing interaction, the RHFB+QRPA model is applied to a calculation of β -decay half-lives of neutron-rich nuclei with $20 \leq Z \leq 50$, extending over the entire r -process path from $N = 50$ to $N = 82$. It is found that the RHFB+QRPA model calculation reproduces the experimental β -decay half-lives for neutron-rich nuclei, especially for nuclei with half-lives less than one second. Using the calculated β -decay half-lives of neutron-rich nuclei, a remarkable speeding up of r -matter flow is predicted. This leads to an enhancement of r -process abundances of elements with $A \gtrsim 140$.

This work was partly supported by the Major State 973 Program 2013CB834400, the National Natural Science Foundation of China under Grant Nos. 10975008, 11105006, 11175001, 11175002, 11075066, and 11205004, the 211 Project of Anhui University under Grant No. 02303319-33190135, the Fundamental Research Funds for Central Universities under Contract No. lzujbky-2012-k07, the Program for New Century Excellent Talents in University, and the mzos-project 1191005-1010.

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- [1] D. Lunney, J. M. Pearson, C. Thibault, Rev. Mod. Phys. **75**, 1021 (2003).
 - [2] E. Nácher *et al.*, Phys. Rev. Lett. **92**, 232501 (2004) .
 - [3] V. Tripathi *et al.*, Phys. Rev. Lett. **101**, 142504 (2008).
 - [4] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957).

- [5] Y.-Z. Qian and G. J. Wasserburg, Phys. Rep. **442**, 237 (2007).
- [6] K. Langanke and G. Martínez-Pinedo, Rev. Mod. Phys. **75**, 819 (2003).
- [7] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. **105**, 1413 (1957).
- [8] I. S. Towner and J. C. Hardy, Rep. Prog. Phys. **73**, 046301 (2010).
- [9] H. Z. Liang, N. Van Giai, and J. Meng, Phys. Rev. C **79**, 064316 (2009).
- [10] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003) updated with data from National Nuclear Data Center, <http://www.nndc.bnl.gov>.
- [11] P. T. Hosmer *et al.*, Phys. Rev. Lett. **94**, 112501 (2005).
- [12] J. Pereira *et al.*, Phys. Rev. C **79**, 035806 (2009).
- [13] S. Nishimura *et al.*, Phys. Rev. Lett. **106**, 052502 (2011).
- [14] N. Nishimura, T. Kajino, G. J. Mathews, S. Nishimura, and T. Suzuki, Phys. Rev. C **85**, 048801 (2012).
- [15] E. Fermi, Z. Phys. **88**, 161 (1934).
- [16] G. Martínez-Pinedo and K. Langanke, Phys. Rev. Lett. **83**, 4502 (1999).
- [17] T. Suzuki, T. Yoshida, T. Kajino, and T. Otsuka, Phys. Rev. C **85**, 015802 (2012).
- [18] P. Möller, J. R. Nix, and K.-L. Kratz, At. Data Nucl. Data Tables **66**, 131 (1997).
- [19] I. N. Borzov, and S. Goriely, Phys. Rev. C **62**, 035501 (2000).
- [20] J. Engel, M. Bender, J. Dobaczewski, W. Nazarewicz, and R. Surman, Phys. Rev. C **60**, 014302 (1999).
- [21] I. N. Borzov *et al.*, Z. Phys. **A355**, 117 (1996).
- [22] J. Meng, H. Toki, S. G. Zhou, S. Q. Zhang, W. H. Longa, and L. S. Geng, Prog. Part. Nucl. Phys. **57**, 470 (2006).
- [23] D. Vretenar, A. V. Afanasjev, G. A. Lalazissis, and P. Ring, Phys. Rep. **409**, 101 (2005).
- [24] T. Nikšić, D. Vretenar, and P. Ring, Prog. Part. Nucl. Phys. **66**, 519 (2011).
- [25] H. Z. Liang, P. W. Zhao, L. L. Li, and J. Meng, Phys. Rev. C **83**, 011302(R) (2011).
- [26] N. Paar, T. Nikšić, D. Vretenar, and P. Ring, Phys. Rev. C **69**, 054303 (2004).
- [27] T. Nikšić, T. Marketin, D. Vretenar, N. Paar, and P. Ring, Phys. Rev. C **71**, 014308 (2005).
- [28] T. Marketin, D. Vretenar, and P. Ring, Phys. Rev. C **75**, 024304 (2007).
- [29] H. Z. Liang, N. Van Giai, and J. Meng, Phys. Rev. Lett. **101**, 122502 (2008).
- [30] H. Z. Liang, P. W. Zhao, and J. Meng, Phys. Rev. C **85**, 064302 (2012).

- [31] W. H. Long, P. Ring, N. Van Giai, and J. Meng, Phys. Rev. C **81**, 024308 (2010).
- [32] J.-P. Ebran, E. Khan, D. Peña Arteaga, and D. Vretenar, Phys. Rev. C **83**, 064323 (2011).
- [33] J. F. Berger, M. Girod, and D. Gogny, Nucl. Phys. **A428**, 23 (1984).
- [34] W. H. Long, N. Van Giai, and J. Meng, Phys. Lett. **B640**, 150 (2006).
- [35] P. Sarriguren and J. Pereira, Phys. Rev. C **81**, 064314 (2010).
- [36] L. S. Geng, H. Toki, and J. Meng, Prog. Theor. Phys. **113**, 785 (2005).
- [37] B. Sun, F. Montes, L. S. Geng, H. Geissel, Yu. A. Litvinov, and J. Meng, Phys. Rev. C **78**, 025806 (2008).
- [38] Z. M. Niu, B. Sun, and J. Meng, Phys. Rev. C **80**, 065806 (2009).